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BANDSLIP R1.2 Theory and User's Guide

by Michael A. Minnicino

ARL-TR-3598 September 2005

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ARL-TR-3598 **September 2005**

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE ***(DD-MM-YYYY)*** September 2005	**2. REPORT TYPE** Final		**3. DATES COVERED (From - To)** July 2005
4. TITLE AND SUBTITLE BANDSLIP R1.2 Theory and User's Guide			**5a. CONTRACT NUMBER**
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Michael A. Minnicino (ARL)			**5d. PROJECT NUMBER** 622618.H80
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Weapons and Materials Research Directorate Aberdeen Proving Ground, MD 21005-5069			**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-3598
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			
13. SUPPLEMENTARY NOTES			

14. ABSTRACT

A code was produced by Sandia National Laboratories, Albuquerque, New Mexico, in the late 1980s to predict sub-projectile spin rates for slip-banded munitions. In a slip-banded munition, the projectile rotates at a spin rate less than that of the rifling because of slip between the obturator and the projectile body while obturation of the propellant gases is maintained. The code, called "BANDSLIP[1]," was written in FORTRAN (Formula Translator) and used software and libraries that were consistent with the programming methods at SNL generally used at the time. With the passage of time and changes in hardware and software, it became desirable to rewrite the code to be more compatible with modern computing techniques. The original BANDSLIP algorithm, referenced as BANDSLIP R1.0, has been incrementally modified, augmented, and validated. The end product of the rewriting process is referenced as BANDSLIP R1.2. The purpose of this report is to provide a guide for using BANDSLIP R1.2, while providing documentation of the theory behind the original and new versions of the code.

[1]BANDSLIP is not an acronym.

15. SUBJECT TERMS
bandslip; desppun; dode; munition

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Michael A. Minnicino
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	35	**19b. TELEPHONE NUMBER** (*Include area code*) 410-306-1919

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Background

The original BANDSLIP R1.0 was developed by Nielan and Benedetti of Sandia National Laboratories, Albuquerque, New Mexico, as a computational tool used to predict the dynamic behavior of "de-spun" munitions (*1*). BANDSLIP R1.0 was distributed to the U.S. Army Ballistics Research Laboratory[1] in 1989 and was later successfully used to qualitatively predict the dynamic behavior of a 105-mm de-spun munition with the use of different slip-band designs (*2*).

A munition is said to be de-spun when the munition's angular velocity is significantly less than its band's angular velocity; thus, the band slips on the munition, thus the name "slip band." With the emergence of smart munitions that possess advanced guidance for dynamic targeting capabilities, de-spun munitions are seen as the best approach for survivability of these fin-stabilized, canard-guided munitions because of the reduced aerodynamic loads on the fins and canards.

2. Theory

The cross section of a typical slip-band design is shown in figure 1. From this figure, it is seen that the slip band rides on a section of material denoted as the band seat, which is outlined in the figure by dashed lines. From experience, it is recommended that the slip band ride on a polymer band seat for performance and reliability reasons (*2*). The polymer band seat is permanently fixed to the sub-projectile and therefore, the band seat dynamic measurements (angular rotation, angular velocity, etc.) are equivalent to the attached sub-projectile. A design using a distinct band seat material relative to the slip band and the sub-projectile is referred to as a two-piece slip-band design. Conversely, if the band seat is provided by the sub-projectile material, it is referred to as a one-piece slip-band design. The base pressure is the pressure acting normal to the munition's surfaces rear of the band because of the propellant deflagration. The tube pressure is realized after the slip band is radially compressed when it passes through the gun's forcing cone and subsequently remains radially confined by the gun barrel inner wall. The effect of the tube pressure is to provide a compressive radial stress between the slip band and the band seat. The magnitude of the induced radial stress is difficult to determine and is not constant along its length (x-direction). However, since the code uses rigid body equations of motion (EoM), the mean radial-induced stress is prescribed as the input to BANDSLIP.

[1] Now the U.S. Army Research Laboratory

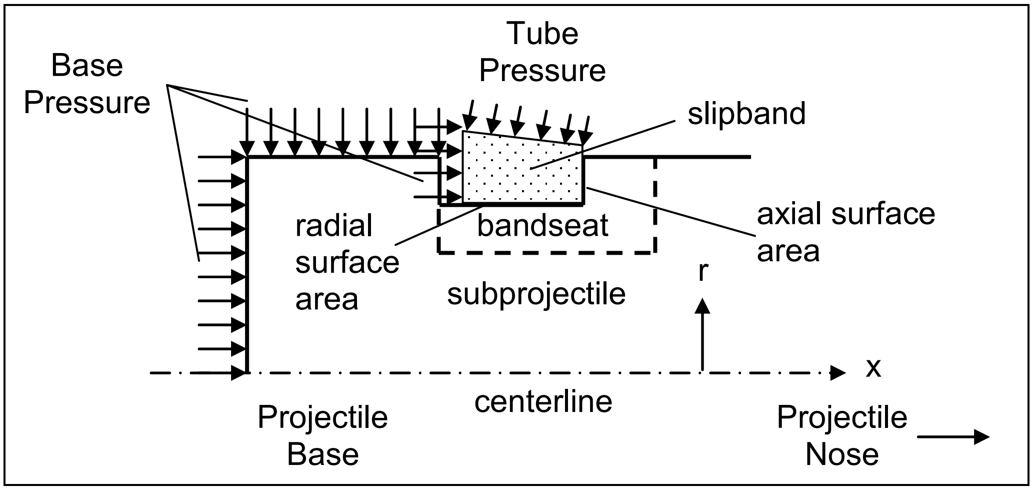

Figure 1. Typical de-spun munition geometry cross section illustrating the areas where the base pressure acts upon the tube pressure and the axial and radial surfaces that transfer torque to the sub-projectile.

The dynamic behavior of a de-spun munition is predicted via rigid body EoM coupled with a kinematic constraint equation. The slip band is kinematically constrained to rotate in accordance with the gun barrel rifling. With the subscripts "b" to denote band seat and "s" to denote slip band, the kinematic constraint is defined by equation 1, in which $\ddot{\theta}_s$ is the slip band's angular velocity, P_{base} is the base pressure, A_{base} is the munition's base area, R_{gun} is the gun's bore radius, η is the lead of the rifling measured in calibers per revolution, and m is the total munition's mass. As previously noted, the base pressure acts on the munition's surfaces rear of the slip band; however, the net area over which the base pressure acts is the base area that is defined as the total projected area of the munition base onto a plane whose normal is coincidental with the centerline axis. The band seat, thus sub-projectile, moves according to the EoM condition specified by equation 2, in which $\ddot{\theta}_s$ is the sub-projectile's angular velocity, T is the applied torque, and I_{proj} is the moment of inertia with respect to the sub-projectile's axis of symmetry, i.e., its centerline axis.

$$\ddot{\theta}_s(t) = \frac{\pi A_{base} P_{base}(t)}{R_{gun}\,\eta\, m} \tag{1}$$

$$\ddot{\theta}_b(t) = \frac{T(t)}{I_{proj}} \tag{2}$$

The transmitted torque T(t) of equation 2 is calculated as shown in figure 2. As shown by this figure, BANDSLIP compares the radial compressive contact pressure induced by gun barrel to the base pressure. When the base pressure magnitude is larger than the radial contact pressure, the slip band is unseated or "lifted," and the torque transmitted by the radial surface is lost. When the torque required to rotate the munition with the band cannot be maintained by the axial and radial surfaces, slip occurs. The relative velocity between these surfaces generates heat. The heat generation enables the melting of the slip band and/or the band seat materials at their interface. The low viscosity melted liquid interface cannot support torsion loads, thereby

allowing slip. The munition's angular velocity is therefore limited to its angular velocity when both axial and radial surfaces have melted or the radial surface has lifted and the axial surface has melted. The one-dimensional (1-D) thermal model used to predict the onset of melting at the slip-band-band-seat interface is shown in figure 3. The 1-D heat transfer problem is governed by equation 3 with the interface boundary condition given in equation 4. Using the subscripts "b" to denote band seat and "s" to denote slip band, U is temperature, α is the material's thermal diffusivity, k is the material's thermal conductivity. The heat flux, q″, is the product of the friction coefficient, μ, the contact pressure, P (which differs between the axial and radial interfaces), and the relative linear velocity, v_{rel}, between the slip band and band seat. The dummy spatial variable ξ is used since this model is valid for both the axial (1D in x coordinate) and radial (1-D in r = y coordinate) interfaces.

$$\frac{\partial^2 U(\xi,t)}{\partial \xi^2} = \frac{1}{\alpha}\frac{\partial U(\xi,t)}{\partial t} \tag{3}$$

$$-k_s \frac{\partial U_s(0,t)}{\partial \xi} + k_b \frac{\partial U_b(0,t)}{\partial \xi} = q^{"} = \mu P v_{rel}(t) \tag{4}$$

Observation of equations 3 and 4 reveals that

- slip band and band seat are assumed to have sufficient thickness in order to be treated as semi-infinite materials;
- all work at the slip-band-to-band-seat interface generates heat;
- slip band and band seat are assumed to be homogeneous and isotropic;
- perfect contact is assumed in the heat generation term.

Solving the 1-D heat equation explicitly for the temperature at the interface (ξ = 0) yields

$$U(\xi=0,t) = U(\xi=0,t-\Delta t) + q^{"}\sqrt{\frac{\Delta t}{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}} \tag{5}$$

in which U(0,t) is the current temperature at the interface, and U(0,t-Δt) is the previous temperature interface. The development of equation 5 using the Laplace transform method is presented in appendix A (*3*).

With equations 1 through 5, the torque transmitted from the slip band to the band seat, thus the sub-projectile, can be calculated according to the program logic shown in figure 2. Note that the model depicted in figure 1 shows that the axial and radial traction surfaces are normal and therefore independent of each other. This implicit assumption is brought to the foreground in view of the expression for the effective torque transmitted shown in figure 2. Therefore a slip-band design featuring non-constant coordinate surfaces, e.g., a radially tapered interface, cannot be accounted for because of the formulation in which the transmitted torque is calculated. Given the effective transmitted torque, the band seat's angular acceleration is calculated by equation 2.

The angular acceleration's anti-derivatives, i.e., angular velocity and angular rotation, are subsequently found via the method of first differences. For example, the angular velocity is found by

$$\dot{\theta}(t) = \dot{\theta}(t - \Delta t) + \ddot{\theta}(t)\Delta t \qquad (6)$$

Similarly, the angular rotation is calculated by

$$\theta(t) = \theta(t - \Delta t) + \dot{\theta}(t)\Delta t \qquad (7)$$

Depending on the type of analysis, BANDSLIP R1.2 outputs certain dynamic parameters to ASCII (American standard code for information exchange) files for post-processing.

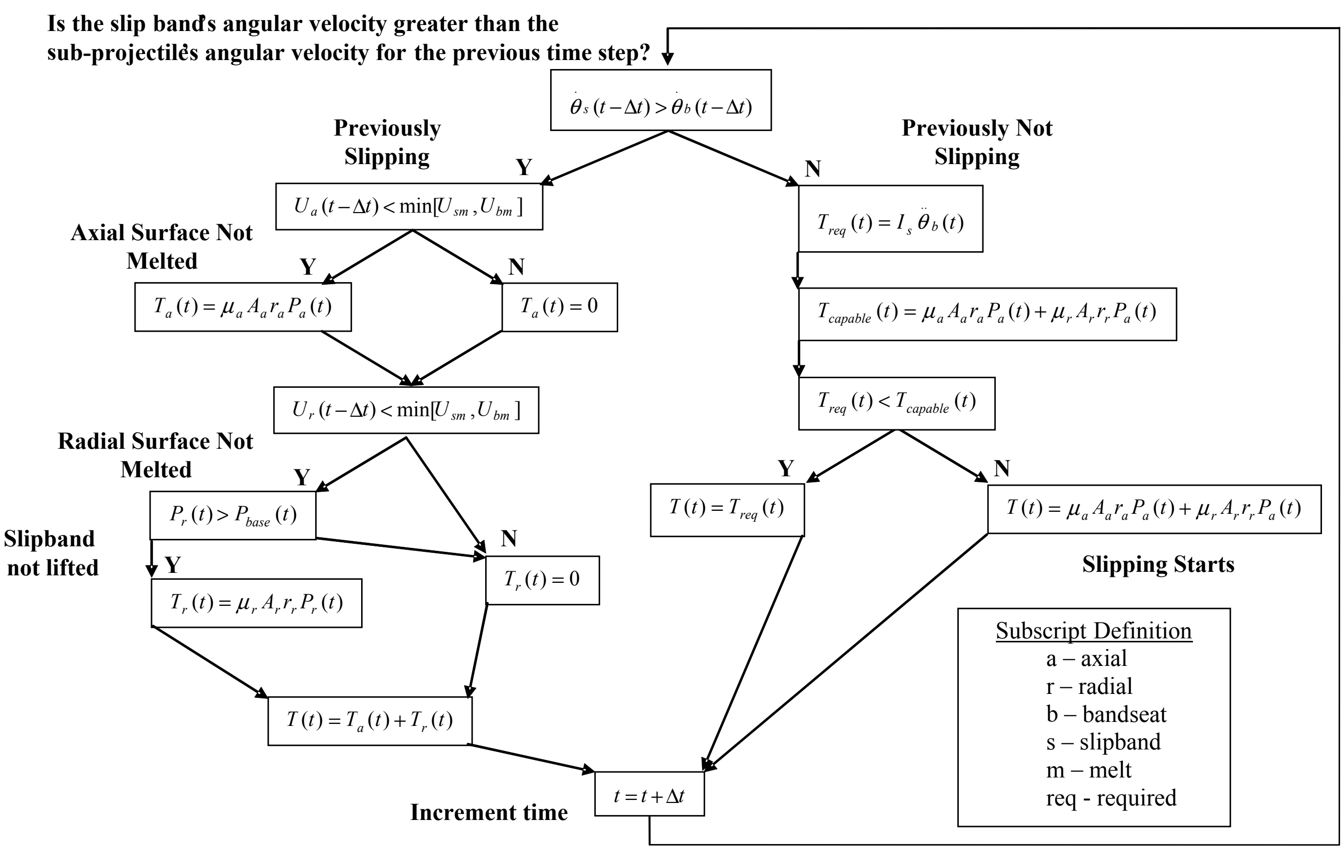

Figure 2. Program logic for calculating the transmitted torque T(t) to the band seat, thus sub-projectile, from the slip band.

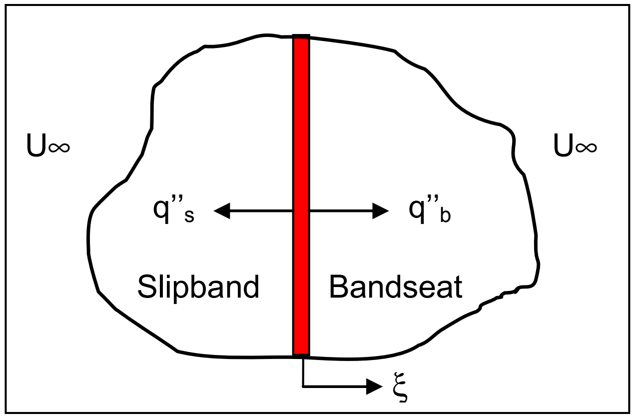

Figure 3. Thermal 1-D model used to predict the onset of melting at the slip-band-band-seat interface.

3. User's Guide

Operating BANDSLIP R1.2 is straightforward. To run BANDSLIP R1.2, the source file **bandslipR12.f** must be successfully compiled (creating bandslipR12.obj), then simply linked against itself to create **bandslipR12.exe** (as opposed to the original version of the code, BANDSLIP R1.2 does not require linking against external libraries). The file **bandslipR12.exe** can be executed on a personal computer running a Microsoft (MS) operating system by the following procedure:

1. Find and execute **bandslipR12.exe**:

a. Open an MS command window. From the command window, change directories to where **bandslipR12.exe**, the analysis input file (AI file), and the base pressure input file (PI file) are located. Enter ***bandslipR12.exe*** at the command prompt.

OR

b. Locate **bandslipR12.exe** on the PC and double click the file to begin execution.

2. Upon doing this, the user will be prompted to enter the name of the AI file. A sample AI file is given in appendix B. Enter the name of this AI file, e.g., ***testband.in***, at the prompt. The user will then be prompted to enter the name of the PI file.

3. The PI file is a two-column delimited ASCII file containing time versus base pressure data. A sample PI file is presented in appendix C. Enter the name of the PI file, e.g., ***testband.press***, at the prompt. BANDSLIP R1.2 will then run to completion if no errors exist in the input.

The analysis input file is divided into four main sections. The first section is referred to as the analysis header section. The input in this section determines the type of analysis and the

controlling parameters for each of these analyses. There are two types of BANDSLIP R1.2 analyses: SWEEP and HISTORY. A SWEEP analysis sweeps through the defined limits of the radial band pressure and slip-band-to-band-seat friction coefficients, or simply the friction coefficients, and reports the slip band design's initial slip time, lift time, axial and radial melt time, required base pressure needed to induce slip, sub-projectile rotation at exit, and sub-projectile angular velocity at exit. The SWEEP analysis produces a family of solutions, from which the user with empirical knowledge of achievable tube pressure and friction coefficients can select the appropriate conditions to study in further detail. An example of a SWEEP analysis output is given in appendix D.

A HISTORY analysis outputs the time-dependent dynamic behavior of the band seat, thus the affixed sub-projectile based on a uniquely specified radial band pressure and friction coefficient. During a HISTORY analysis, BANDSLIP R1.2 reports the pressure, slip band angular acceleration and velocity, sub-projectile angular acceleration and velocity, axial interface temperature, radial interface temperature, and the distance traveled for each time step to the bandslip.out1 file. BANDSLIP R1.2 reports pressure, the transmitted torque, the maximum available torque, the required torque, the torque transmitted across the axial interface, the torque transmitted by the radial interface, and the projectile axial velocity for each step to the bandslip.out2 file. An example of each HISTORY analysis output file is shown in appendix E.

A new feature in BANDSLIP R1.2 is that ability to explicitly define the slip band and band seat materials in the analysis header section by a material identification number that is uniquely associated with a material defined in the material database section. This feature allows multiple materials to be defined in an AI file, allowing the user to easily switch materials for a given geometry.

The second section is the analysis parameters section where unit conversion factors are located. The third section is the analysis geometry section where the slip-band geometry is defined as well as the munition's moment of inertia with respect to the centerline axis. Note that this assumes that the location where the moment of inertia is taken resides on the centerline axis, i.e., the munition is axisymmetric. The last section is the material database. This section defines the relevant material properties needed for the analysis: density, thermal conductivity, specific heat, and melt temperature. A table defining the AI file input, units, and descriptions is presented in appendix F.

4. Summary

BANDSLIP R1.2 has successfully been revised and is now able to be run independent of external libraries or subroutines. The theory and program logic of BANDSLIP R1.0 and R1.2 have been documented. A basic user's guide has been presented for BANDSLIP R1.2.

Additionally, validated example analysis input and pressure input files with their corresponding SWEEP and HISTORY output files are included in the appendices for reference. Finally, a variable table given in appendix F details each of the input variables and units and provides a short description.

5. References

1. Nielan, P.E.; Benedetti, G.A. *Spin Rate Prediction for Projectiles with Slipping Obturators*; Presentation Handout; Ballistic Research Laboratory: Aberdeen Proving Ground, MD, 7 September 1988.

2. Kaste, R.P. *Development of a Design Methodology for Slip band Obturators*; BRL-TR-3297; Ballistic Research Laboratory: Aberdeen Proving Ground, MD, 22 November 1991.

3. Research & Education Association. *Handbook of Mathematical, Scientific, and Engineering Formulas, Tables, Functions, Graphs, Transforms*. Piscataway, NJ, 1992.

Appendix A. Development of Equation 5 – Temperature at Slip-Band-Band-Seat Interface

Equation 5 gives the temperature at the slip-band-band-seat interface as

$$U(\xi=0,t)=U(t-\Delta t)+q^{"}\sqrt{\frac{\Delta t}{\pi(k_s\rho_s c_s+k_b\rho_b c_b)}} \tag{A-1}$$

Beginning with the governing partial differential equation and boundary condition given in equations 3 and 4 and taking the Laplace transform yields

$$\frac{\partial^2 U(\xi,t)}{\partial\xi^2}=\frac{1}{\alpha}\frac{\partial U(\xi,t)}{\partial t}\overset{L}{\Leftrightarrow}\frac{\partial^2 \bar{U}(\xi,s)}{\partial\xi^2}=\frac{1}{\alpha}(s\bar{U}(\xi,s)-U_\infty) \tag{A-2}$$

and

$$k_s\frac{\partial U_s(0,t)}{\partial\xi}-k_b\frac{\partial U_b(0,t)}{\partial\xi}=q^{"}\overset{L}{\Leftrightarrow}k_s\frac{\partial \bar{U}_s(0,s)}{\partial\xi}-k_b\frac{\partial \bar{U}_b(0,s)}{\partial\xi}=\frac{q^{"}}{s} \tag{A-3}$$

Rearranging equation A-2 in Laplace space results in the ordinary differential equation

$$\frac{d^2\bar{U}(\xi,s)}{d\xi^2}-\frac{1}{\alpha}s\bar{U}(\xi,s)=-\frac{1}{\alpha}U_\infty \tag{A-4}$$

which has the solution

$$\bar{U}_s(\xi,s)=\frac{1}{\alpha}U_\infty+Ae^{\frac{\sqrt{s}}{\sqrt{\alpha_s}}\xi}+Be^{\frac{-\sqrt{s}}{\sqrt{\alpha_s}}\xi}\text{, for }\xi\ge 0 \tag{A-5a}$$

$$\bar{U}_s(\xi,s)=\frac{1}{\alpha}U_\infty+Ce^{\frac{\sqrt{s}}{\sqrt{\alpha_b}}\xi}+De^{\frac{-\sqrt{s}}{\sqrt{\alpha_b}}\xi}\text{, for }\xi\le 0 \tag{A-5b}$$

The condition as $\xi\to\infty$, namely, $U(\xi\to\infty,t)\to U_\infty$, implies that $\bar{U}(\xi\to\infty,s)\to U_\infty$; therefore, the coefficients A=D=0 of equations A-5a and A-5b, respectively. Also, imposing the condition that the slip band and band seat have identical temperatures at the interface, i.e., $U_s(\xi=0,t)$ and $U_b(\xi=0,t)$, prescribes B = C. The remaining unknown coefficient B, thus C, is chosen so that it satisfies the boundary condition at $\xi=0$ defined by equation A-2.

$$k_s\frac{\partial}{\partial y}[\frac{1}{\alpha}U_\infty+Be^{\frac{-\sqrt{s}}{\sqrt{\alpha_s}}y}]-k_b\frac{\partial}{\partial y}[\frac{1}{\alpha}U_\infty+Be^{\frac{\sqrt{s}}{\sqrt{\alpha_s}}y}]=$$

$$k_s\sqrt{\frac{s}{\alpha_s}}Be^{\frac{-\sqrt{s}}{\sqrt{\alpha_s}}\xi}]+k_b\sqrt{\frac{s}{\alpha_s}}Be^{\frac{\sqrt{s}}{\sqrt{\alpha_s}}\xi}]=B\sqrt{s}\left[\frac{k_s}{\alpha_s}+\frac{k_b}{\alpha_b}\right]=\frac{q^{"}}{s} \tag{A-6}$$

Solving for B yields

$$B = C = \frac{q''}{s^{3/2}}\left[\frac{k_s}{\alpha_s} + \frac{k_s}{\alpha_b}\right] = \frac{q''}{s^{3/2}}\left[\frac{1}{\sqrt{k_s\rho_s c_s + k_b\rho_b c_b}}\right] \tag{A-7}$$

Substituting the expression for B and C = B into equations A-5a and A-5b, respectively, and taking the inverse Laplace transform using the transform tables found in (*3*) yields

$$U_s(x,t) = U_\infty + \frac{2q''}{\sqrt{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}}\left[\sqrt{t}e^{-\xi^2/(4\alpha_s t)} - \frac{\xi}{\sqrt{\alpha_s}}erfc\left(\frac{\xi}{2\sqrt{\alpha_s t}}\right)\right] \tag{A-8a}$$

$$U_b(x,t) = U_\infty + \frac{2q''}{\sqrt{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}}\left[\sqrt{t}e^{-\xi^2/(4\alpha_b t)} - \frac{\xi}{\sqrt{\alpha_b}}erfc\left(\frac{\xi}{2\sqrt{\alpha_b t}}\right)\right] \tag{A-8b}$$

At $\xi=0$

$$U_s(\xi=0,t) = U_b(\xi=0,t) = U_\infty + \frac{2q''\sqrt{t}}{\sqrt{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}} \tag{A-9}$$

For the numerical analysis, as we step through time

$$U(\xi=0,\Delta t) = U_\infty + \frac{2q''\sqrt{\Delta t}}{\sqrt{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}}, \qquad t_1=\Delta t \tag{A-10a}$$

$$U(\xi=0,2\Delta t) = U_\infty + \frac{2q''\sqrt{2\Delta t}}{\sqrt{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}}, \qquad t_2=2\Delta t \tag{A-10b}$$

The difference between t_2 and t_1 is

$$U(\xi=0,2\Delta t) - U(\xi=0,\Delta t) = \frac{2q''\sqrt{2\Delta t - \Delta t}}{\sqrt{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}} \tag{A-11}$$

Finally, rearranging and recasting the equation in a more general form yields the expression for the interface temperature at time t as

$$U(\xi=0,t) = U(\xi=0,t-\Delta t) + \frac{2q''\sqrt{\Delta t}}{\sqrt{\pi(k_s\rho_s c_s + k_b\rho_b c_b)}} \tag{A-12}$$

Appendix B. Sample BANDSLIP R1.2 Analysis Input File (*testband.in*)

```
     sweep                              !  analtype = sweep or history
    0.0333    0.2664    0.0333          !    mu_min    mu_max   mu_step
       0.0 3.448e+08 3.448e+07          ! p_rad_min p_rad_max p_radstep
 1.034e+08       0.1       0.1          !     p_rad      mu_a      mu_r
    7.45e2 1.5355e-2  6.829e-3          ! xdot_exit texit_est     tpeak
         1         3                    ! bandMatID seatMatID       <->
!======================================================================
!-------------------------------------------------Analysis Parameters
    6.3e+1   2.50e-4          !   nparray      step          !
   2.82e+2                    !    u_init       <->          !
   1.45e-4     0.737          !  psi_fact torq_fact          !
    1000.0                    ! time_fact       <->          !
       1.8    -459.0          ! Tfactmult  Tfactadd          !
     3.278   1.59e-1          ! len_fact   ang_fact          !
!-------------------------------------------------Geometry-!
   1.66e-1                    !        Is       <->          !
  2.595e-3  1.917e-2          !    A_rear    A_base          !
 2.5027e-3 7.4676e-2          !    area_a     rad_a          !
 1.7238e-2 7.2009e-2          !    area_r     rad_r          !
    5.2070                    !barrel len       <->          !
     2.0e1  7.812e-2          !     twist        rs          !
  5.442e+1                    !total mass       <->          !
!-------------------------------------------------MAT DB --!----------
         1                    !    mat_ID                    !  NYLON
    1.1e+3    1.1e+3          !     rho_a     rho_r          !
    2.3e-1    2.3e-1          !       k_a       k_r          !
    1.9e+3    1.9e+3          !       c_a       c_r          !
    5.3e+2    5.3e+2          !   umelt_a   umelt_r          !
!----------------------------------------------------------!----------
         2                    !    mat_ID                    !  PP
    1.1e+3    1.1e+3          !     rho_a     rho_r          !
    2.3e-1    2.3e-1          !       k_a       k_r          !
    1.9e+3    1.9e+3          !       c_a       c_r          !
    4.3e+2    4.3e+2          !   umelt_a   umelt_r          !
!----------------------------------------------------------!----------
         3                    !    mat_ID                    !  ALUMINUM
    9.0e+2    9.0e+2          !     rho_a     rho_r          !
    1.2e+2    1.2e+2          !       k_a       k_r          !
    9.6e+2    9.6e+2          !       c_a       c_r          !
    9.2e+2    9.2e+2          !   umelt_a   umelt_r          !
!--------------------------------------------------------------------
```

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Appendix C. Sample BANDSLIP R1.2 Pressure Input File (*testband.press*)

```
    .000e-3       .000e+6
    .250e-3      1.154e+6
    .500e-3      1.809e+6
    .750e-3      2.686e+6
   1.000e-3      3.916e+6
   1.250e-3      5.604e+6
   1.500e-3      7.883e+6
   1.750e-3     10.910e+6
   2.000e-3     14.875e+6
   2.250e-3     20.000e+6
   2.500e-3     26.545e+6
   2.750e-3     34.813e+6
   3.000e-3     45.145e+6
   3.250e-3     57.924e+6
   3.500e-3     73.349e+6
   3.750e-3     91.921e+6
   4.000e-3    114.098e+6
   4.250e-3    139.598e+6
   4.500e-3    169.049e+6
   4.750e-3    202.469e+6
   5.000e-3    230.608e+6
   5.250e-3    255.084e+6
   5.500e-3    277.800e+6
   5.750e-3    297.676e+6
   6.000e-3    313.748e+6
   6.250e-3    325.397e+6
   6.500e-3    332.373e+6
   6.750e-3    334.766e+6
   7.000e-3    332.969e+6
   7.250e-3    327.700e+6
   7.500e-3    319.752e+6
   7.750e-3    309.786e+6
   8.000e-3    298.463e+6
   8.250e-3    286.341e+6
   8.500e-3    273.866e+6
   8.750e-3    261.375e+6
   9.000e-3    249.112e+6
   9.250e-3    237.245e+6
   9.500e-3    225.881e+6
   9.750e-3    215.082e+6
  10.000e-3    204.877e+6
  10.250e-3    195.272e+6
  10.500e-3    186.256e+6
  10.750e-3    177.809e+6
  11.000e-3    165.844e+6
  11.250e-3    153.802e+6
  11.500e-3    143.044e+6
  11.750e-3    133.401e+6
  12.000e-3    124.729e+6
      .            .
      .            .
  12.250e-3    116.907e+6
  12.500e-3    109.829e+6
  12.750e-3    103.405e+6
  13.000e-3     97.558e+6
  13.250e-3     92.222e+6
  13.500e-3     87.339e+6
  13.750e-3     82.859e+6
  14.000e-3     78.739e+6
  14.250e-3     74.941e+6
  14.500e-3     71.432e+6
  14.750e-3     68.184e+6
  15.000e-3     65.525e+6
  15.250e-3     62.000e+6
  15.500e-3     59.000e+6
```

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Appendix D. Sample SWEEP Analysis Output File Generated From *testband.in* and *testband.press*

prad	**mu**	**tslip**	**tlift**	**tmelt_a**	**tmelt_r**	**pslip**	**ths**	**thsdot**
0.00	0.03	0.25	0.00	4.75	999000.00	167.33	0.01	1.27
4999.60	0.03	2.00	2.75	5.00	999000.00	2156.88	0.04	3.51
9999.20	0.03	2.75	3.50	5.00	999000.00	5047.89	0.07	6.14
14998.80	0.03	3.00	4.00	5.00	999000.00	6546.03	0.11	9.14
19998.40	0.03	3.25	4.25	5.25	999000.00	8398.98	0.14	12.06
24998.00	0.03	3.50	4.75	5.25	999000.00	10635.61	0.19	16.68
29997.60	0.03	3.75	5.00	5.50	999000.00	13328.55	0.23	20.73
34997.20	0.03	4.00	5.25	5.50	999000.00	16544.21	0.27	24.83
39996.80	0.03	4.00	5.50	5.75	999000.00	16544.21	0.32	29.75
44996.40	0.03	4.25	6.00	5.75	5.75	20241.71	0.37	34.83
49996.00	0.03	4.25	999000.00	6.00	5.75	20241.71	0.39	37.34
prad	mu	tslip	tlift	tmelt_a	tmelt_r	pslip	ths	thsdot
0.00	0.07	0.25	0.00	4.50	999000.00	167.33	0.02	2.02
4999.60	0.07	2.75	2.75	4.50	999000.00	5047.89	0.05	4.41
9999.20	0.07	3.25	3.50	4.75	999000.00	8398.98	0.10	8.30
14998.80	0.07	3.75	4.00	5.00	999000.00	13328.55	0.15	12.90
19998.40	0.07	4.25	4.25	5.25	999000.00	20241.71	0.19	16.60
24998.00	0.07	4.5	4.75	5.50	999000.00	24512.11	0.27	24.34
29997.60	0.07	4.75	5.00	5.50	999000.00	29358.01	0.32	29.20
34997.20	0.07	4.75	5.25	5.75	999000.00	29358.01	0.38	35.66
39996.80	0.07	5.25	5.50	6.00	999000.00	36987.19	0.45	43.02
44996.40	0.07	5.5	6.00	6.50	999000.00	40281.00	0.59	58.29
49996.00	0.07	5.75	999000.00	7.00	7.00	43163.02	0.85	89.27
prad	mu	tslip	tlift	tmelt_a	tmelt_r	pslip	ths	thsdot
0.00	0.23	0.25	0.00	4.00	999000.00	167.33	0.05	4.31
4999.60	0.23	2.75	2.75	4.25	999000.00	5047.89	0.08	7.20
9999.20	0.23	3.50	3.50	4.50	999000.00	10635.61	0.13	11.10
14998.80	0.23	4.00	4.00	4.75	999000.00	16544.21	0.18	15.79
19998.40	0.23	4.25	4.25	5.00	999000.00	20241.71	0.22	19.96
24998.00	0.23	4.75	4.75	5.25	999000.00	29358.01	0.30	27.81
29997.60	0.23	5.00	5.00	5.50	999000.00	33438.17	0.36	34.08
34997.20	0.23	5.25	5.25	5.75	999000.00	36987.19	0.43	41.08
39996.80	0.23	5.50	5.50	6.00	999000.00	40281.00	0.50	48.72
44996.40	0.23	6.00	6.00	6.50	999000.00	45493.46	0.65	65.61
49996	0.23	999000.00	999000.00	999000.00	999000.00	0.14	1.71	257.03
prad	mu	tslip	tlift	tmelt_a	tmelt_r	pslip	ths	thsdot
0.00	0.27	0.25	0.00	4.00	999000.00	167.33	0.06	4.93
4999.60	0.27	2.75	2.75	4.25	999000.00	5047.89	0.09	7.84
9999.20	0.27	3.50	3.50	4.50	999000.00	10635.61	0.14	11.75
14998.80	0.27	4.00	4.00	4.75	999000.00	16544.21	0.19	16.45
19998.40	0.27	4.25	4.25	5.00	999000.00	20241.71	0.23	20.75
24998.00	0.27	4.75	4.75	5.25	999000.00	29358.01	0.31	28.48
29997.60	0.27	5.00	5.00	5.50	999000.00	33438.17	0.37	34.83
34997.20	0.27	5.25	5.25	5.75	999000.00	36987.19	0.44	41.90
39996.80	0.27	5.50	5.50	6.00	999000.00	40281.00	0.51	49.61
44996.40	0.27	6.00	6.00	6.50	999000.00	45493.46	0.66	66.60
49996	0.27	999000.00	999000.00	999000.00	999000.00	0.14	1.71	257.03

! the following are the same for all runs	
! exit time	14.49999
! band exit spin speed	257.0304
! band exit rotation	1.710064
! exit velocity	2635.095

Appendix E. Sample HISTORY Analysis Output Files bandslip.out1 and bandslip.out2 Generated From *testband.in* and *testband.press*

bandslip.out1 Output File

```
!
! radial pressure =  0.14993E+05
! friction coefficient =    0.10000
!         t           p     thbddot    thsddot     thbdot     thsdot     temp_a     temp_r          w
  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.486E+02  0.486E+02  0.000E+00
  0.250E+00  0.167E+03  0.130E+03  0.130E+03  0.325E-01  0.325E-01  0.486E+02  0.486E+02  0.833E-04
  0.500E+00  0.262E+03  0.204E+03  0.204E+03  0.834E-01  0.834E-01  0.486E+02  0.486E+02  0.297E-03
  0.750E+00  0.389E+03  0.302E+03  0.302E+03  0.159E+00  0.159E+00  0.486E+02  0.486E+02  0.705E-03
  0.100E+01  0.568E+03  0.441E+03  0.441E+03  0.269E+00  0.269E+00  0.486E+02  0.486E+02  0.139E-02
  0.125E+01  0.813E+03  0.631E+03  0.631E+03  0.427E+00  0.427E+00  0.486E+02  0.486E+02  0.249E-02
  0.150E+01  0.114E+04  0.888E+03  0.888E+03  0.649E+00  0.649E+00  0.486E+02  0.486E+02  0.415E-02
  0.175E+01  0.158E+04  0.123E+04  0.123E+04  0.956E+00  0.956E+00  0.486E+02  0.486E+02  0.660E-02
  0.200E+01  0.216E+04  0.168E+04  0.168E+04  0.138E+01  0.138E+01  0.486E+02  0.486E+02  0.101E-01
  0.225E+01  0.290E+04  0.225E+04  0.225E+04  0.194E+01  0.194E+01  0.486E+02  0.486E+02  0.151E-01
  0.250E+01  0.385E+04  0.299E+04  0.299E+04  0.269E+01  0.269E+01  0.486E+02  0.486E+02  0.220E-01
  0.275E+01  0.505E+04  0.392E+04  0.392E+04  0.367E+01  0.367E+01  0.486E+02  0.486E+02  0.314E-01
  0.300E+01  0.655E+04  0.508E+04  0.508E+04  0.494E+01  0.494E+01  0.486E+02  0.486E+02  0.440E-01
  0.325E+01  0.840E+04  0.652E+04  0.652E+04  0.657E+01  0.657E+01  0.486E+02  0.486E+02  0.609E-01
  0.350E+01  0.106E+05  0.826E+04  0.826E+04  0.863E+01  0.863E+01  0.486E+02  0.486E+02  0.830E-01
  0.375E+01  0.133E+05  0.104E+05  0.104E+05  0.112E+02  0.112E+02  0.486E+02  0.486E+02  0.112E+00
  0.400E+01  0.165E+05  0.128E+05  0.212E+04  0.144E+02  0.118E+02  0.486E+02  0.486E+02  0.149E+00
  0.425E+01  0.202E+05  0.157E+05  0.259E+04  0.184E+02  0.124E+02  0.176E+03  0.486E+02  0.196E+00
  0.450E+01  0.245E+05  0.190E+05  0.314E+04  0.231E+02  0.132E+02  0.434E+03  0.486E+02  0.255E+00
  0.475E+01  0.294E+05  0.228E+05  0.376E+04  0.288E+02  0.141E+02  0.890E+03  0.486E+02  0.329E+00
  0.500E+01  0.334E+05  0.260E+05  0.000E+00  0.353E+02  0.141E+02  0.890E+03  0.486E+02  0.419E+00
  0.525E+01  0.370E+05  0.287E+05  0.000E+00  0.425E+02  0.141E+02  0.890E+03  0.486E+02  0.528E+00
  0.550E+01  0.403E+05  0.313E+05  0.000E+00  0.503E+02  0.141E+02  0.890E+03  0.486E+02  0.657E+00
  0.575E+01  0.432E+05  0.335E+05  0.000E+00  0.587E+02  0.141E+02  0.890E+03  0.486E+02  0.808E+00
  0.600E+01  0.455E+05  0.353E+05  0.000E+00  0.675E+02  0.141E+02  0.890E+03  0.486E+02  0.981E+00
  0.625E+01  0.472E+05  0.366E+05  0.000E+00  0.767E+02  0.141E+02  0.890E+03  0.486E+02  0.118E+01
   .
   .
   .
```

bandslip.out2 Output File

```
!
! radial pressure =  0.14993E+05
! friction coefficient =      0.10000
!          t           p     tor_tot     tor_max     tor_req       tor_a       tor_r        wdot
   0.000E+00   0.000E+00   0.000E+00   0.946E+04   0.000E+00   0.000E+00   0.946E+04   0.000E+00
   0.250E+00   0.167E+03   0.100E+03   0.948E+04   0.100E+03   0.165E+02   0.946E+04   0.333E+00
   0.500E+00   0.262E+03   0.157E+03   0.949E+04   0.157E+03   0.258E+02   0.946E+04   0.855E+00
   0.750E+00   0.389E+03   0.233E+03   0.950E+04   0.233E+03   0.384E+02   0.946E+04   0.163E+01
   0.100E+01   0.568E+03   0.339E+03   0.952E+04   0.339E+03   0.559E+02   0.946E+04   0.276E+01
   0.125E+01   0.813E+03   0.486E+03   0.954E+04   0.486E+03   0.800E+02   0.946E+04   0.438E+01
   0.150E+01   0.114E+04   0.683E+03   0.957E+04   0.683E+03   0.113E+03   0.946E+04   0.665E+01
   0.175E+01   0.158E+04   0.945E+03   0.962E+04   0.945E+03   0.156E+03   0.946E+04   0.980E+01
   0.200E+01   0.216E+04   0.129E+04   0.967E+04   0.129E+04   0.212E+03   0.946E+04   0.141E+02
   0.225E+01   0.290E+04   0.173E+04   0.974E+04   0.173E+04   0.286E+03   0.946E+04   0.199E+02
   0.250E+01   0.385E+04   0.230E+04   0.984E+04   0.230E+04   0.379E+03   0.946E+04   0.275E+02
   0.275E+01   0.505E+04   0.302E+04   0.996E+04   0.302E+04   0.497E+03   0.946E+04   0.376E+02
   0.300E+01   0.655E+04   0.391E+04   0.101E+05   0.391E+04   0.645E+03   0.946E+04   0.506E+02
   0.325E+01   0.840E+04   0.502E+04   0.103E+05   0.502E+04   0.827E+03   0.946E+04   0.673E+02
   0.350E+01   0.106E+05   0.636E+04   0.105E+05   0.636E+04   0.105E+04   0.946E+04   0.885E+02
   0.375E+01   0.133E+05   0.797E+04   0.108E+05   0.797E+04   0.131E+04   0.946E+04   0.115E+03
   0.400E+01   0.165E+05   0.163E+04   0.163E+04   0.989E+04   0.163E+04   0.000E+00   0.148E+03
   0.425E+01   0.202E+05   0.199E+04   0.199E+04   0.121E+05   0.199E+04   0.000E+00   0.188E+03
   0.450E+01   0.245E+05   0.241E+04   0.241E+04   0.146E+05   0.241E+04   0.000E+00   0.237E+03
   0.475E+01   0.294E+05   0.289E+04   0.289E+04   0.175E+05   0.289E+04   0.000E+00   0.296E+03
   0.500E+01   0.334E+05   0.000E+00   0.000E+00   0.200E+05   0.000E+00   0.000E+00   0.362E+03
   0.525E+01   0.370E+05   0.000E+00   0.000E+00   0.221E+05   0.000E+00   0.000E+00   0.436E+03
   0.550E+01   0.403E+05   0.000E+00   0.000E+00   0.241E+05   0.000E+00   0.000E+00   0.516E+03
   0.575E+01   0.432E+05   0.000E+00   0.000E+00   0.258E+05   0.000E+00   0.000E+00   0.602E+03
   0.600E+01   0.455E+05   0.000E+00   0.000E+00   0.272E+05   0.000E+00   0.000E+00   0.692E+03
   0.625E+01   0.472E+05   0.000E+00   0.000E+00   0.282E+05   0.000E+00   0.000E+00   0.786E+03
   0.650E+01   0.482E+05   0.000E+00   0.000E+00   0.288E+05   0.000E+00   0.000E+00   0.882E+03
    .
    .
    .
```

Appendix F. BANDSLIP R1.2 Variable Table

Parameter	Units	Description
Analysis Header Section		
analtype	sweep | history	Selection dictates type of BANDSLIP R1.2 analysis
mu_min	-	Lower bound for coefficient of friction for Sweep Analysis (SA)
mu_max	-	Upper bound for coefficient of friction for SA
mu_step	-	Incremental step size for coefficient of friction for SA
p_rad_min	Pa	Lower bound for radial contact pressure for SA
p_rad_max	Pa	Upper bound radial contact pressure for SA
p_rad_step	Pa	Incremental radial contact pressure for SA
p_rad	Pa	Radial contact pressure for History Analysis (HA)
mu_a	-	Axial coefficient of friction for HA
mu_r	-	Radial coefficient of friction for HA
xdot_exit	m/sec	Subprojectile muzzle velocity
texit_est	sec	Munition estimated exit time
tpeak	sec	Pressure pulse peak time
Analysis Parameters Section		
nparray	-	Number of points in supplied pressure-vs.-time curve
step	-	Time step size (should be close to temporal space of pressure-time curve)
u_init	K	Initial temperature
psi_fact		Scale Factor (SF) used to convert Pascal to [PSI] or other unit for output only
torq_fact		SF used to convert Nm to [ft-lbf] or other unit for output only
time_fact		SF used to convert seconds to [msec] or other unit for output only
Tfactmult		Multiplied part of temperature conversion equation, K to [°F] for output only
Tfactadd		Additive part of temperature conversion equation, K to [°F] t for output only
len_fact		SF used to convert meters to [inch] or other unit for output only
ang_fact	rev/rad	SF used to convert radians to revolutions
Analysis Geometry Section		
Is	kg-m^2	Moment of Inertia with respect to projectile and cannon centerline axis
A_rear	m^2	Rear area of projectile
A_base	m^2	Base area of projectile
area_a	m^2	Axial traction surface area
rad_a	m	Effective radius (moment arm) of axial traction
area_r	m^2	Radial traction surface area
rad_r	m	Effective radius (moment arm) of radial traction
barrel_len	m	Cannon barrel length
rs	m	Cannon barrel radius
twist	calibers/rev	Rifling pitch measured in calibers per revolution
total_mass	kg	Mass of band and subprojectile
Material Database Section		
mat_ID	-	Material database ID number
rho_a	kg/m^3	Density of slipband in axial direction
rho_r	kg/m^3	Density of slipband in radial direction
k_a	W/m - K	Material thermal conductivity in axial direction
k_r	W/m - K	Material thermal conductivity in radial direction
c_a	J/kg-K	Material specific heat in axial direction
c_r	J/kg-K	Material specific heat in radial direction
umelt_a	K	Material Melt Termperature in the axial direction
umelt_r	K	Material melt temperature in the radial direction

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